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Non-Destructive Assessment of a Historic Masonry Arch Bridge Using Ground Penetrating Radar and 3D Laser Scanner

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Abstract **– Applications of non-destructive testing methods such as ground penetrating radar (GPR), 3D laser scanners, accelerometer sensors and vibration detecting sensors amongst many others have been used to assess and monitor masonry arch bridge spans (brick and stone) in the past few years. This paper reports the application of high to low frequency GPR antenna systems (2000 MHz, 600 MHz and 200 MHz) and a 3D laser scanner on a historic masonry arch bridge (the Old Bridge, Aylesford - 860 years old) located in Kent, England. The position of different layers of the deck structure was established with the identification of the original stone base of the bridge and location of a number of structural ties (anchors – remedial work carried out previously). Results of the 3D laser scan of the bridge were crucial to initiate long-term monitoring of the structure.**

I. INTRODUCTION

There exist approximately 70,000 masonry arch bridge spans (brick and stone) in the United Kingdom with tens of thousands more throughout Europe. A significant number of these bridges are still in operation and form part of the road and rail network systems in many countries. Masonry arch bridges make use of materials with little or no tensile strength and rely on their ability to resist compression [1]. Although construction of these structures has long been abandoned in the UK, brick arch bridges can be also a viable alternative to steel or concrete bridges. To this effect, construction costs may be slightly greater, whereas maintenance costs are lower; hence, whole life costs are likely to be competitive [2]. Anyhow, the main issue nowadays concerns many of the existing structures that are in desperate need of repair and maintenance [3]. Many of the potential durability concerns are due to the effects of water. Rainwater, floodwater, groundwater or water from damaged pipes within the structure may severely affect the structural stability of arch bridges. Water may wash out fines from the fill, reactions may occur between chemicals dissolved in the water and the mortar or cycles of freezing and thawing may cause damage to brickwork. In addition, these structures are subject to ever increasing traffic levels, speeds and loads that may impair the functionality and the conditions of structural integrity. To keep these assets operational in the future it is therefore necessary to provide effective stewardship and maintenance as well as to understand adequately their special needs [2]. To this purpose, destructive testing methods such as drilling cores [4] and the flat-jack test [5] are used to assess specific properties of the construction materials. On the other hand, non-destructive testing (NDT) methods such as ground penetrating radar (GPR) [6, 7], 3D laser scanners [8], accelerometer sensors and vibration detecting sensors [9] amongst many others have gained momentum for assessing and monitoring such structures more comprehensively. NDT methods allow for a non-intrusive and detailed survey of civil engineering infrastructures. In this regard, they have become popular in the health monitoring of infrastructure heritage assets, where non-intrusive inspections are a key requirement. GPR can provide information on the subsurface; hence the structure can be assessed and interventions planned on purpose. The use of a 3D laser scanner allows for an accurate measurement of the dimensions of the entire bridge as well as for recording the position of all the features (mm accuracy) for future reference.

II. AIMS AND OBJECTIVES

The main aim of this research was to provide structural detailing of the bridge deck in order to install spotlights flush within the upper layer of the pavement without any intrusion on to the historic stonework of a masonry arch bridge. To achieve this aim, the main objectives (pursued using a 2000 MHz GPR system) were:

- to assess the depth of the upper layer of asphalt and its uniformity throughout the surface of the deck;
- to assess the depth to the historic stonework.

A secondary aim of this project was to model the bridge (including the location of reinforcement bars) and initiate the long-term monitoring of the whole structure. To this purpose, low-frequency GPR systems (200 MHz and 600 MHz), tape measuring and a laser scanner were used.

III. THE SURVEY SITE

The Old Bridge at Aylesford (UK) is a multi-span bridge dating from around 1250 (Fig. 1).

The bridge is constructed of local "ragstone" with seven arches including a central segmental arch and six pointed and double-chamfered outer arches. The bridge width is about 4 m between the centres of the stone-coped parapet. The end arches are partly buried by the river bank. The stone piers have cutwaters on the upstream and downstream sides on rebuilt concrete foundations. On each side are octagonal and triangular canted pedestrian refuges resting on buttresses over the piers. Below the bridge is a barge-bed constructed from large baulks of timber. The bridge underwent a major alteration in the early 1800s, when the two central arches were replaced by a single arch of 18 m span, removing a pier to allow passage for larger river traffic [10].

The bridge is closed to cars and motorbikes, although it remains in use for pedestrians, cyclists and horses. It is a scheduled ancient monument under the control of the English Heritage. There is currently no lighting system on the bridge and potential installation was considered in this paper. To this purpose, lights and power cables could be installed within the upper layer of the asphalt without any intrusion to the historic bridge stonework.

IV. EQUIPMENT & SURVEY METHODOLOGIES

A. 2000 MHz antenna system

Data were acquired using the RIS Hi-BrigHT GPR antenna array manufactured by IDS Georadar.

The system consists of two rows of eight double polarized 2000 MHz antennas with 10 cm spacing and allows scanning with a footprint 80 cm wide. The bridge deck was surveyed collecting four longitudinal scans spaced equally, that were performed along the length of the bridge. Transversal scans (i.e.,scans across the bridge) were not collected. For data management purposes, the survey was divided into three 'Zones' (Fig. 2).

Fig. 1. The Old Bridge at Aylesford in Kent, UK.

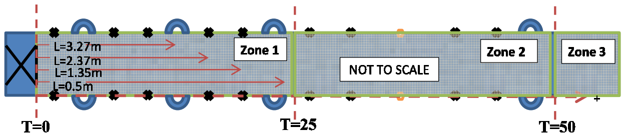

Fig. 2. The Old Bridge: depiction of the survey zones.

B. 200 MHz & 600 MHz dual frequency antenna system

The main purpose of these investigations was to identify reinforcement bars through the bridge structure. To this intent, four scans were performed using the TR Dual-F 200 MHz and 600 MHz antenna system (penetration of 1.5 m and 2.5 m, respectively) from the IDS RIS MF Hi-Mod. The GPR apparatus contains an array of two antennas with frequencies optimized for underground utility detection. The existing reference points (high frequency survey) were considered and the same data acquisition as the high frequency survey over the three areas was carried out.

C. Manual measurements

A multi-stage procedure was followed to approximately locate the positions of the X_i frames in depth with respect to the bridge deck, and distance with respect to the scar in the tarmac. A folding ruler was used to calculate the depth $D_{T,i}$ of the i^{th} targets below the tarmac as follows:

$$D_{T,i} = D_{1,i} - D_{2,i} \tag{1}$$

where $D_{1,i}$ is the depth of the centre of the Xi reinforcement (measured from the top of the wall) and $D_{2,i}$ is the height of the wall above the tarmac at the position of the X_i frame.

D. Laser scanner

A 3D laser scanner Leica P20 was used for the investigation. The accuracy of the equipment at 50 m distance of acquisition is 3 mm, with a standard deviation of 2 mm. Imaging of the system is 5 megapixels per each 17° × 17° colour image. The high resolution scan was made placing the reference targets on the bridge in locations that were visible from multiple measurement positions.

V. MAIN RESULTS & SHORT DISCUSSION

A. 2000 MHz antenna system

Investigations made for the assessment of the entity and development in depth of the surface damage with the 2000 MHz antenna system showed evidence of surface reinstatement at all the three identified zones. The identification of such damage was achieved after analysing B-scan and C-scan maps of the data collected. An example of this analysis is represented in Fig. 3. Results from the 2000 MHz antenna system showed that the thickness of the asphalt layer was not uniform and varied from 3 cm to 12 cm in Zone 1, from 3 cm to 13 cm in Zone 2 and from 4 cm to 12 cm in Zone 3.

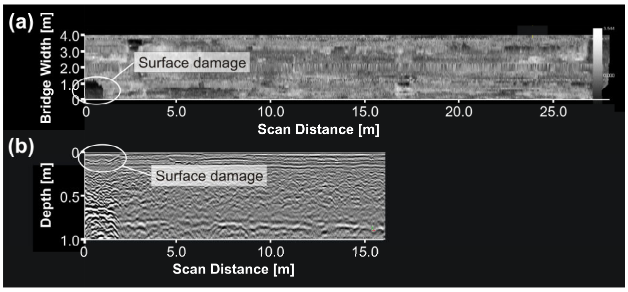

Fig. 3. Surface reinstatement identified in Zone 3 from (a) a C-scan (5 cm deep) and (b) a B-scan view.

Structural detailing showed a second layer of base material beneath the asphalt layer and directly on the top of the stonework. This was likely arranged to avoid irregularities in the stone surface and a uniform distribution of loads at the bottom of the structure.

Overall, the survey carried out with the 2000 MHz antenna system identified a total depth from the bridge surface to the historic stonework as variable across the bridge, with the minimum depth being at the centre of the widest arch.

Depth variations from 29 cm to 53 cm were collected at Zone 1, whereas 29 cm ÷ 53 cm and 26 cm ÷ 73 cm intervals were found at Zone 2 and Zone 3, respectively. It is worth noting that the data related to thicknesses beyond 40 cm of depth could have lower reliability than the data collected for the shallower thicknesses. This is related to the limited penetration of the high-frequency antenna systems at such depths.

The average thickness of the upper asphalt layer was 7 cm. The average total depth from the bridge surface to the historic stonework was 41 cm (Fig. 4).

The considerable variation in the thickness of both layers is shown in Fig. 5. This is likely related to the bridge's construction and the large areas of resurfacing identified.

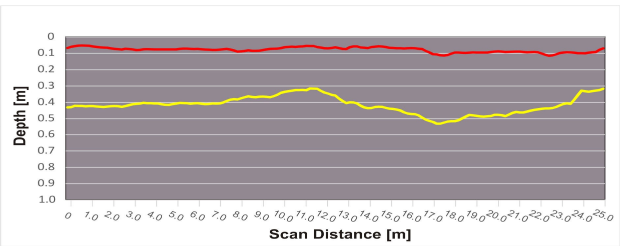

Fig. 4. Average total depth of asphalt (red line) and base layers (yellow line) within the bridge deck area.

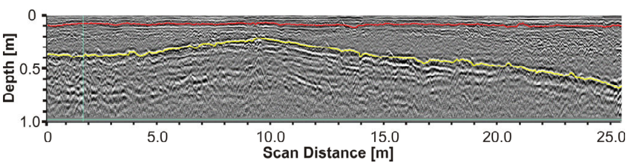

Fig. 5. Layering of the asphalt (red line) and base layers (yellow line) within one scan in Zone 2.

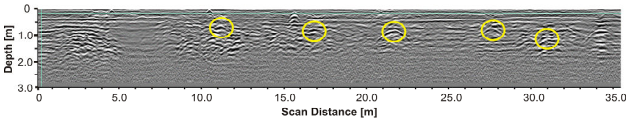

Fig. 6. Reinforcing bars (in circles) identified using the 600 MHz GPR system.

B. 200 MHz and 600 MHz antenna system

With regards to the location of the ties, the 200 MHz and 600 MHz dual frequency antenna system was able to identify the reinforcing bars (Fig. 6). In case the location of these targets was unclear, cross-matching with the data outputs from the manual measurements and the laser scanner equipment were considered for the interpretation of the GPR data.

C. Manual measurements

Locations and depths of the X frames were identified with respect to the X shaped scar in the tarmac (Fig. 7). It is important to note that the measured distances are taken over the curvature of the bridge. This can distort the provided linear representation of the manual measurements and the actual positioning of the X frames on the surface area based on the plan view of Fig. 7.

D. Laser scanner

The 3D Laser scanner allowed to develop the modelling of the whole structure with a mm accuracy. In particular, locations of the ties identified by the GPR systems were confirmed (Fig. 8).

In addition, a database of the entire structure was created for future reference and assessment of the bridge conditions.

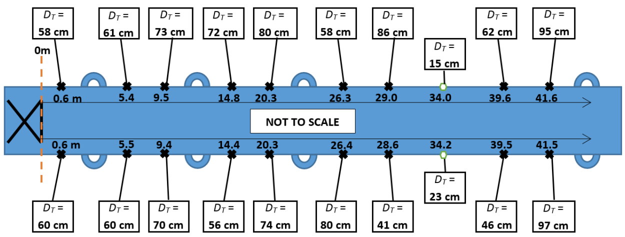

Fig. 7. Overview of the Old Bridge with locations and depths of the reinforcing bars.

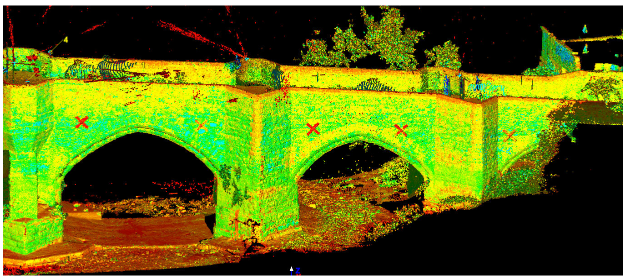

Fig. 8. Reinforcing bars (red crosses) identified by the laser scanner.

VI. CONCLUSION

This paper reports the application of high to low frequency ground penetrating radar (GPR) antenna systems (2000 MHz, 600 MHz and 200 MHz) and a 3D laser scanner on a historic masonry arch bridge (the Old Bridge, Aylesford - 860 years old) located in Kent, England. Results from the 2000 MHz antenna system enlightened that the thickness of the upper asphalt layer was not uniform, with an average value of 7 cm. Similarly, the total depth from the bridge surface to the historic stonework was variable, with an average value equal to 41 cm. The considerable variation in the thickness of both layers was related to the bridge's construction and the large areas of resurfacing identified with the 2000 MHz GPR system. With regards to the location of the ties and the modelling of the whole structure, the 200 MHz and 600 MHz dual frequency antenna system was able to identify the reinforcing bars. Location was confirmed also by the manual measurements and the modelling performed using the 3D laser scanner.

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